Structural Design and Certification of the AMS-02 Magnet Strap Support System

Chris Tutt

Lockheed Martin Space Operations

AMS-02 Critical Design Review

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Introduction

- Overview
- Strap Support System Design
- Strap Support System Verification Plan
  - Testing Plan
  - Analysis Plan
- Correlation Results to Date
- Future Work

Support System Responsibilities

- Straps designed and manufactured by Space Cryomagnetics, Ltd (SCL).
- Strap analysis and verification by Lockheed Martin and SCL.
- Strap testing at several sites
  - Crompton Technology Group (CTG)
  - Rutherford Appleton Laboratories (RAL)
  - Lockheed Martin
  - Johnson Space Center.

Overview

- Magnet strap support system is primary load path between magnet/He tank and flight support structure.
- Straps are nonlinear system which requires specialized analysis and testing.
- Strap stiffness and magnet/He tank mass defines the first few global AMS-02 modes.

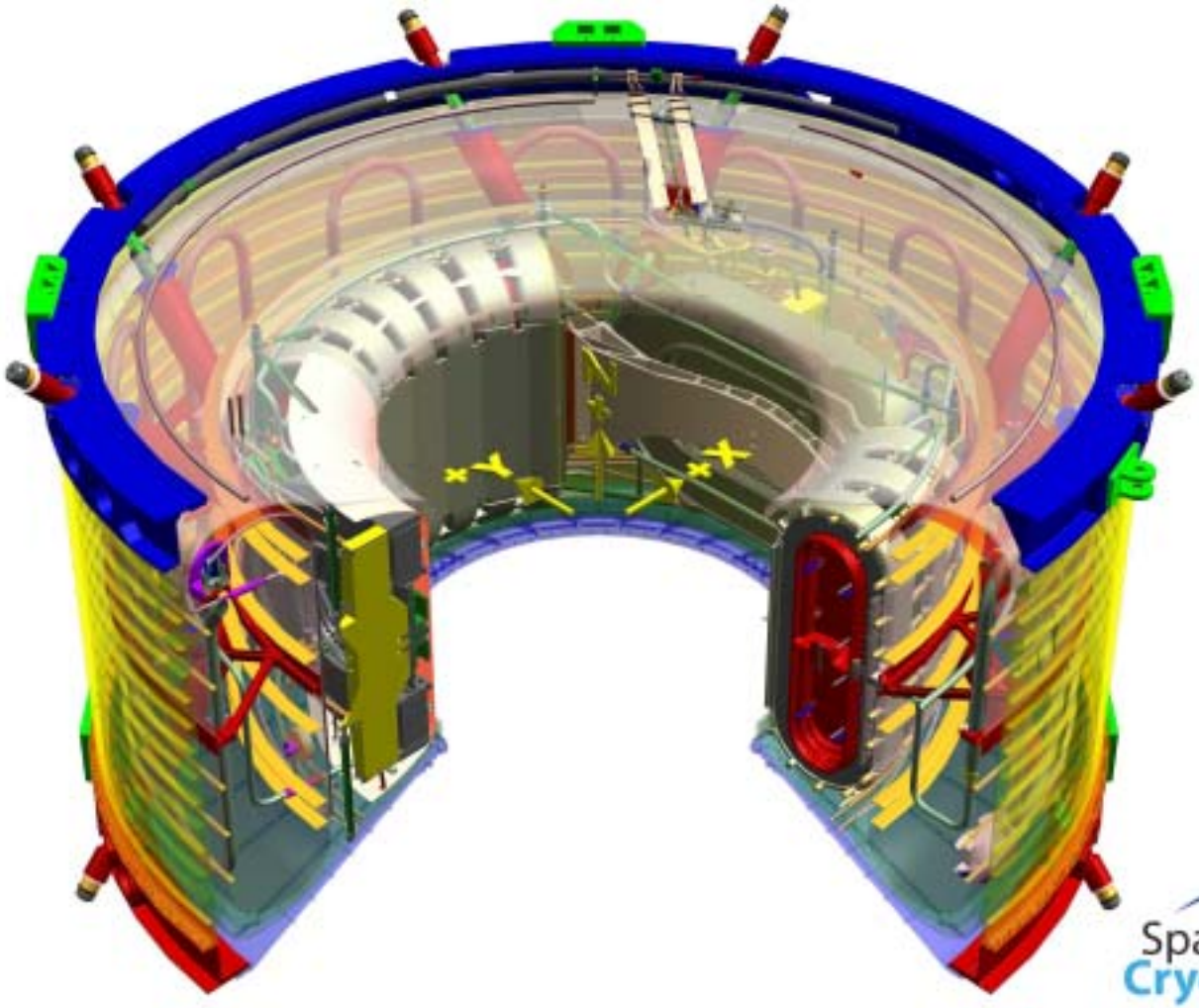
Support System Design Goals

- Superfluid He tank must be maintained at ~1.8K for three-year design lifetime.
- Support system must have minimal parasitic heat load while still resisting launch and landing structural loads.
- System must fit in current Vacuum Case dimensions.

Magnet Support System Design

- AMS-02 cryomagnet and He tank suspended from Vacuum Case by 16 individual strap systems.
- Individual straps contain four composite bands.
- Overall strap system has a nonlinear force-displacement relationship.

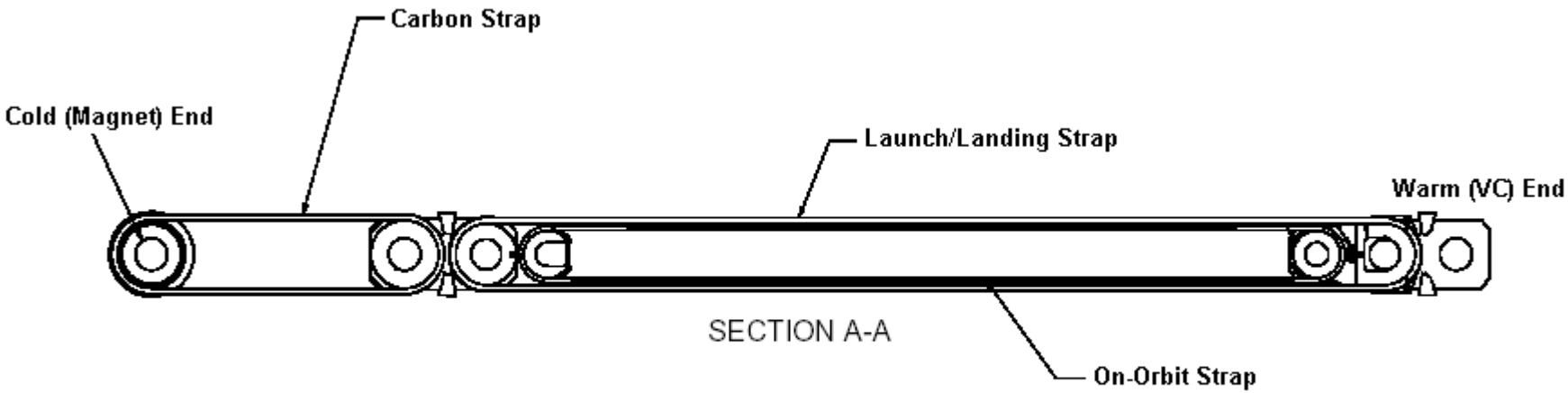
Magnet Support System



Individual Strap Overview

- Individual straps consist of four composite bands.
  - On-orbit strap to support lower level loads.
  - Stiff launch/landing strap to support higher loads.
  - Carbon strap (cold end) and fiberglass bod (warm end) to help reduce heat transfer.
- Belleville washer stack at warm end.
- Two types of straps: C1W1 and C2W2.

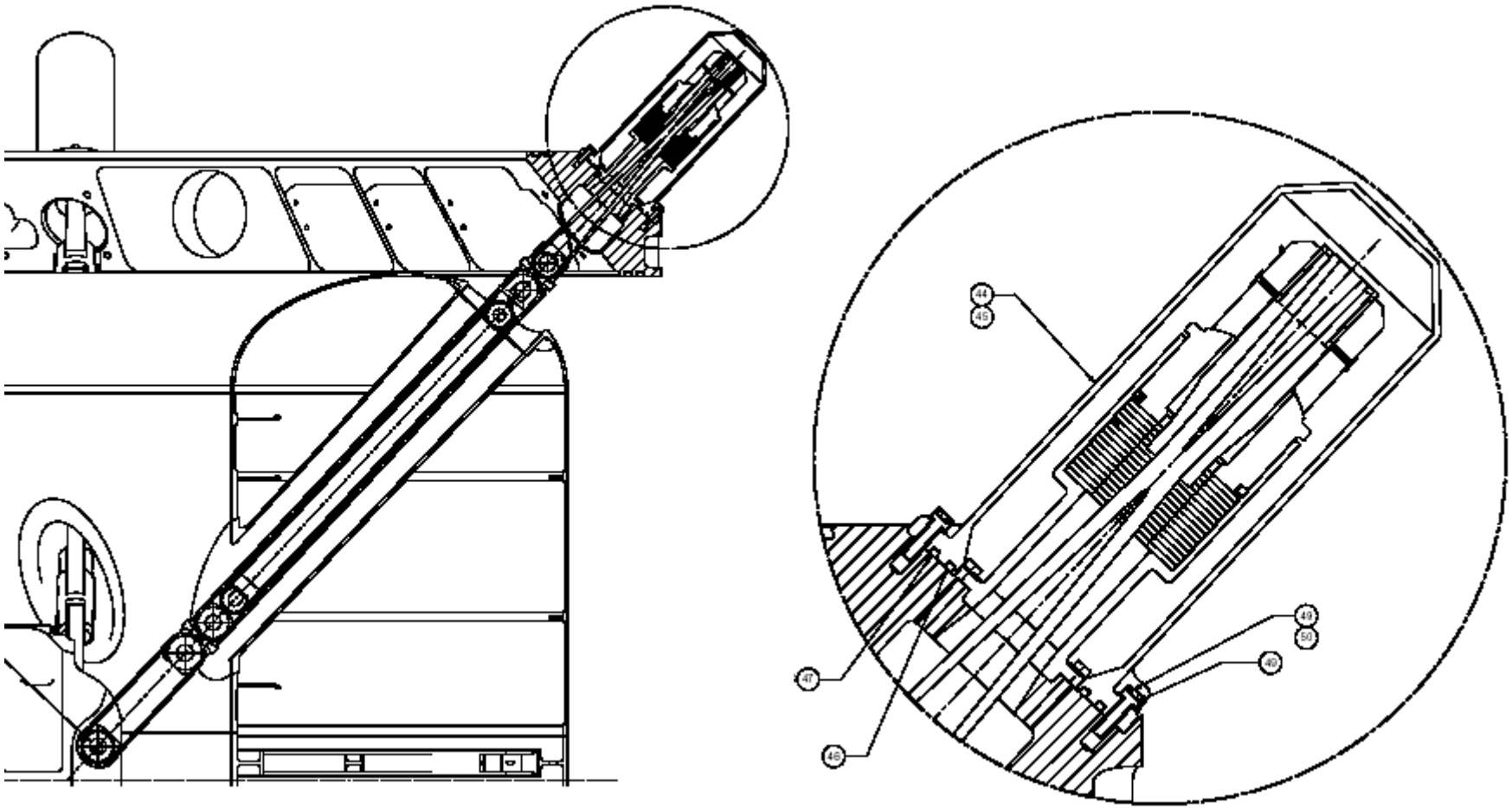
Individual Strap Systems



Strap Photos

Photo courtesy of CTG

Strap "Wineglass" End Fitting



Wineglass Photo

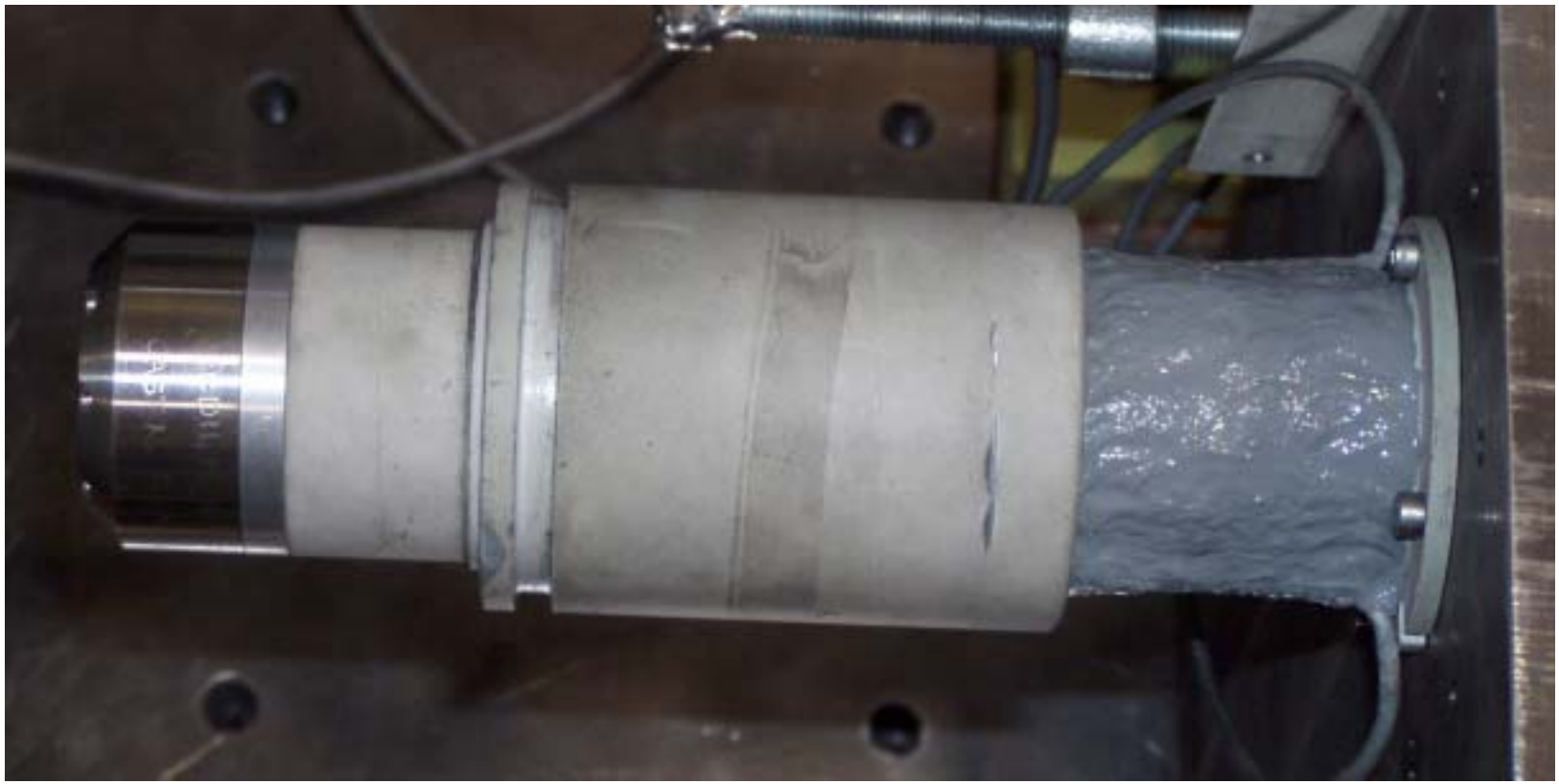
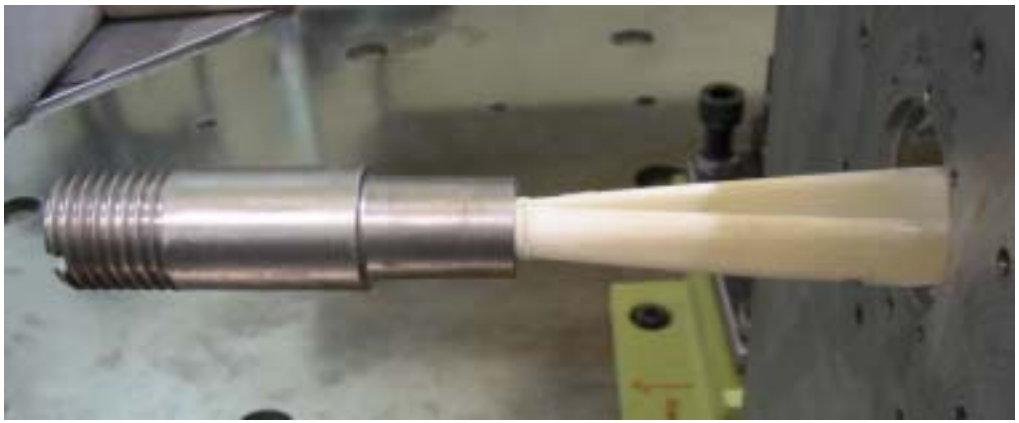


Photo courtesy of C. Lauritzen

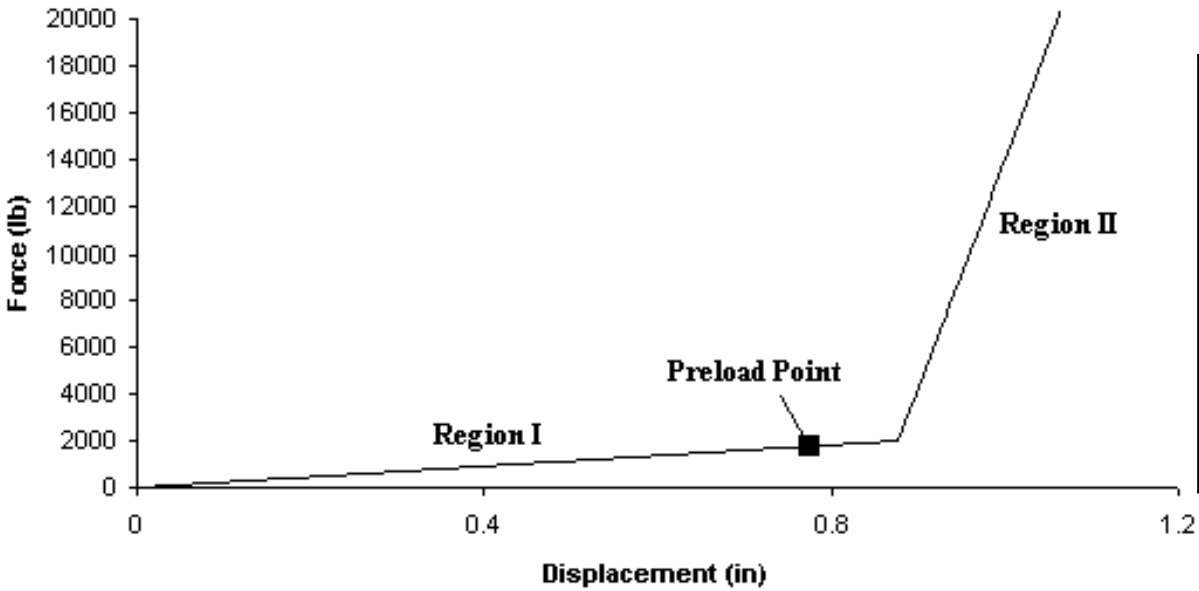
Disassembled End Photos



Strap Nonlinearity

- Straps have a generally bilinear or trilinear force-displacement relationship, based on temperature.
  - Lower region stiffness dominated by Belleville washer stack.
  - Upper region stiffnesses dominated by component band stiffness.
- Strap properties vary with temperature.
  - “Cold” set used when magnet/He tank cooled to cryogenic temperatures.
  - “Warm” set used when magnet/He tank at ambient temperatures.

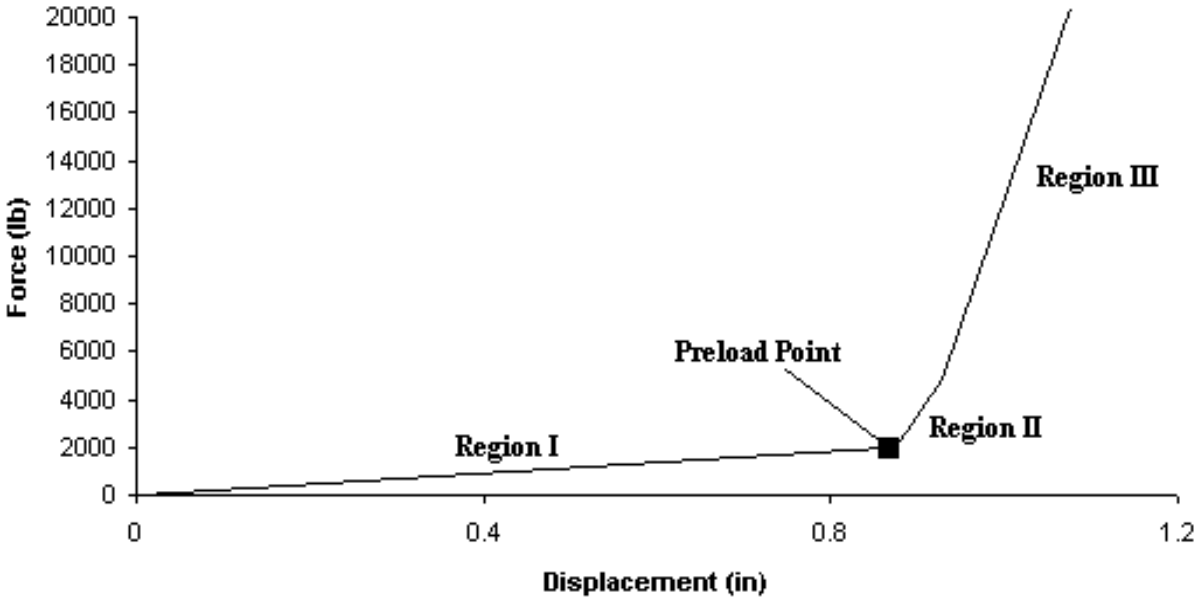
C1W1 Warm Stiffness Curve



Tensile Load	Deflection from Preload Point
0 lb	-0.773”
1753 lb	0”
1989 lb	0.104”
2157 lb	0.107”
26977 lb	0.360”

- Region I stiffness = 2,312 lb/in, Region II stiffness = 81,240 lb/in

C1W1 Cold Stiffness Curve



Tensile Load	Deflection from Preload Point
0 lb	-0.867”
1973 lb	0”
1989 lb	0.007”
4819 lb	0.061”
26977 lb	0.272”

- Region I stiffness 2,262 lb/in, Region II stiffness = 46,238 lb/in, Region III stiffness = 87,207 lb/in.

Strap Verification Plan

- Strap models will be correlated in multiple steps using five separate tests.
- Nonlinear models will be developed for internal project use.
- Linearized model developed and verified for use in the VLA.
  - Linearized model must be shown to envelope loads generated by the nonlinear model.

Strap Testing Plan

- Full straps will undergo six tests:
  - Fatigue Test (complete)
  - Static Test to 1.2x limit load (all flight and test units).
  - 1-D Dynamic Test (complete)
  - Warm Static Failure Test
  - Cold Static Failure Test
  - High-level Sine Sweep Test
- Component bands, Belleville washers, and wineglasses also extensively tested.

Component Band Tests

- Individual component bands static tested at CTG in November 2001.
  - All units were pulled to 1.2x limit load without yielding.
  - Multiple units were then pulled to failure to determine ultimate strength. In each case, failure occurred above 2.0x limit load.
  - Component stiffnesses measured for use in model correlation.

Belleville Washer Tests

- Belleville washer static testing done in England in April/May 2002.
- Multiple washers statically loaded until fully closed to determine force-displacement relationship.
- Further static tests will be done on production washers to verify performance.

Strap Fatigue Test

- Two straps fatigue tested at CTG in August 2002.
- Fatigue spectrum includes all transport, testing, liftoff/landing, and on-orbit events. Details in SVP section 8.2.
- Both straps survived with no detrimental yielding.

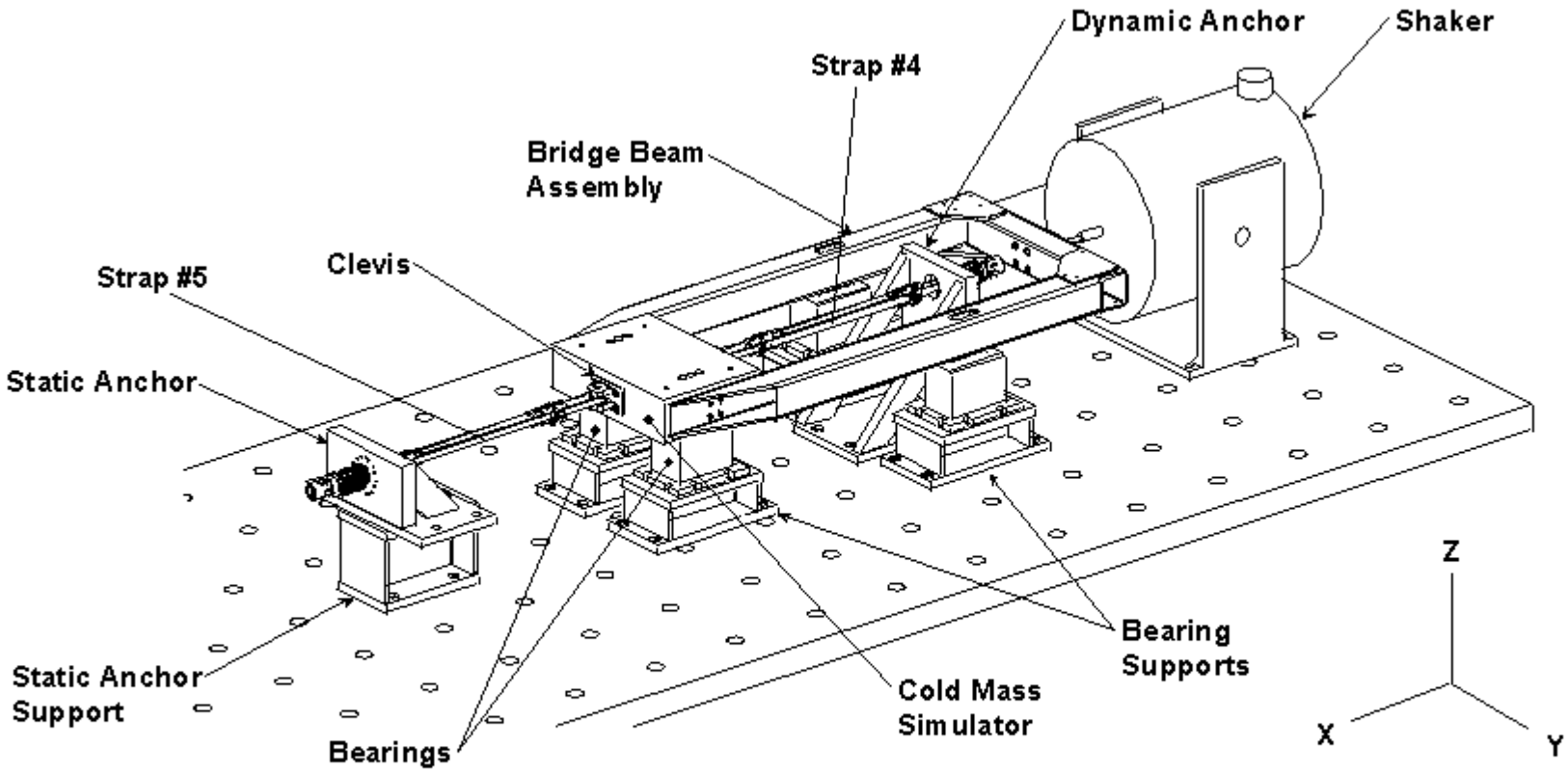
Strap Static Tests

- Two strap static tests were performed at CTG in November 2002 and March 2003.
- Single straps were loaded to 20,225 lb (90 kN) and force-displacement characteristic recorded.
- Data used for strap model correlation and associated perturbation studies.

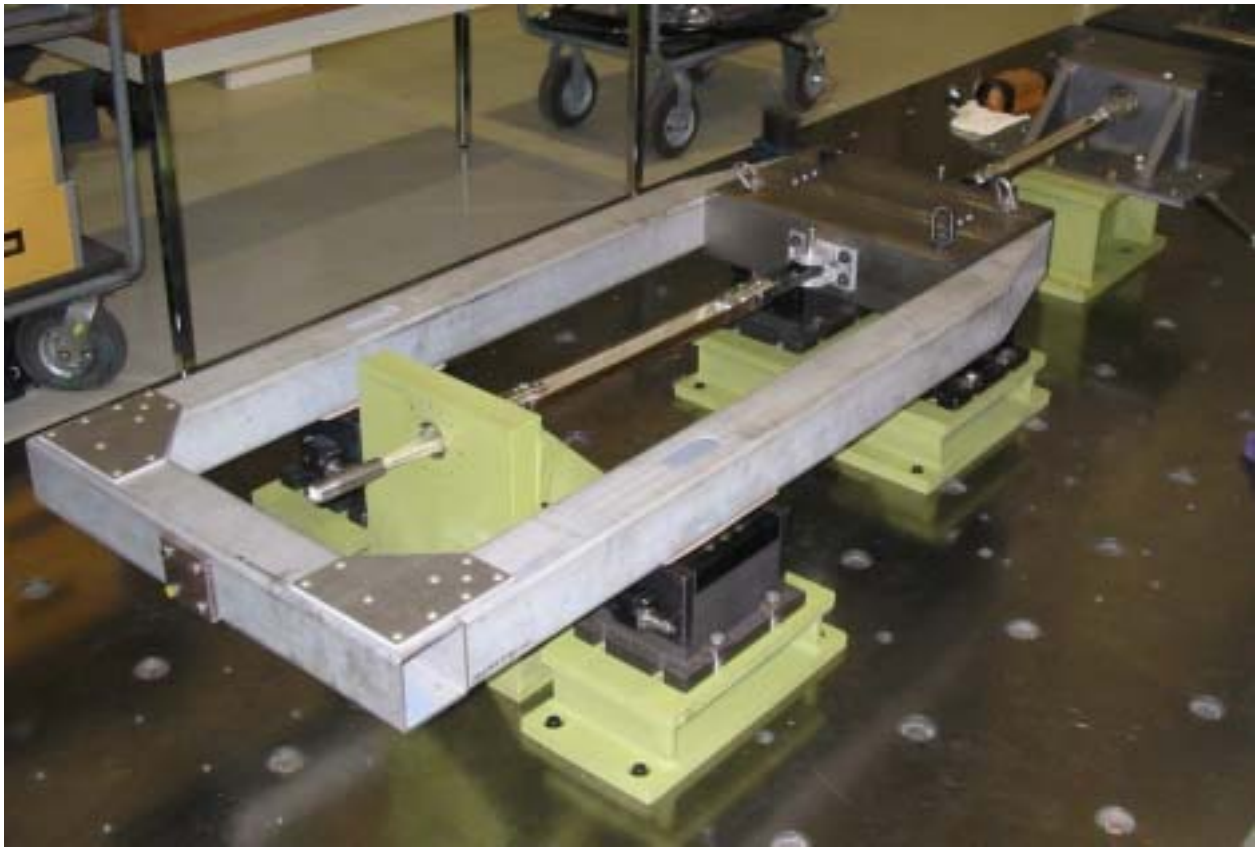
1-D Dynamic Tests

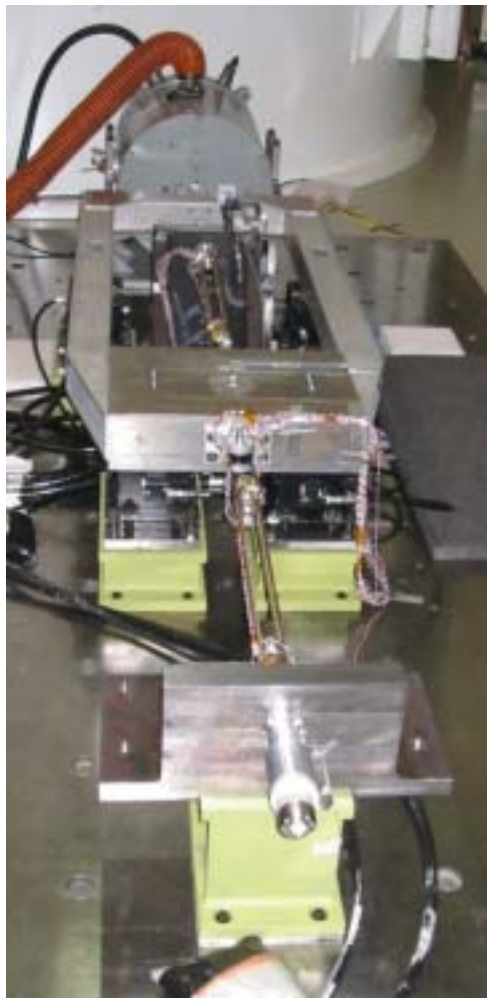
- Simple 1-D strap dynamic tests done at LM-Denver in June 2002, September 2002, and April 2003.
  - Wineglass fitting added after first test.
  - Wineglass fitting coated in Keronite after second test.
- Two straps connected coaxially to 500 lb mass resting on linear bearings.
- Two primary test goals
  - Validate nonlinear analysis methodology
  - Obtain frequency response data for correlation of individual straps.

1-D Dynamic Test Configuration



1-D Dynamic Test Photos

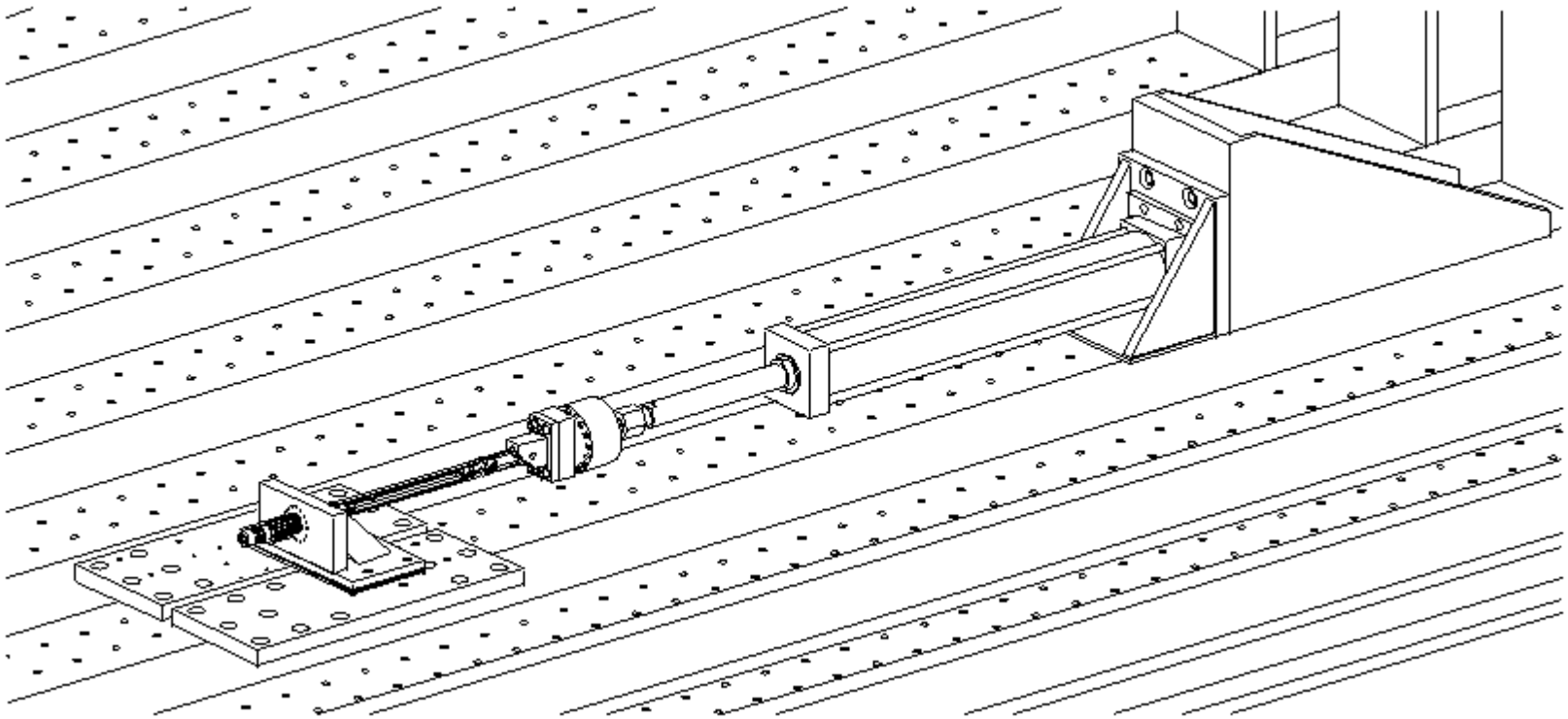




Warm Strap Static Failure Test

- Strap static failure test scheduled for JSC Building 13 in June 2003.
- Single strap will be pulled to failure.
- Primary goal is to determine actual strap ultimate load.
- Secondary goal is confirming force-displacement relationship for correlation purposes.
- If strap end clevises do not fail during the test, these will be tested individually.

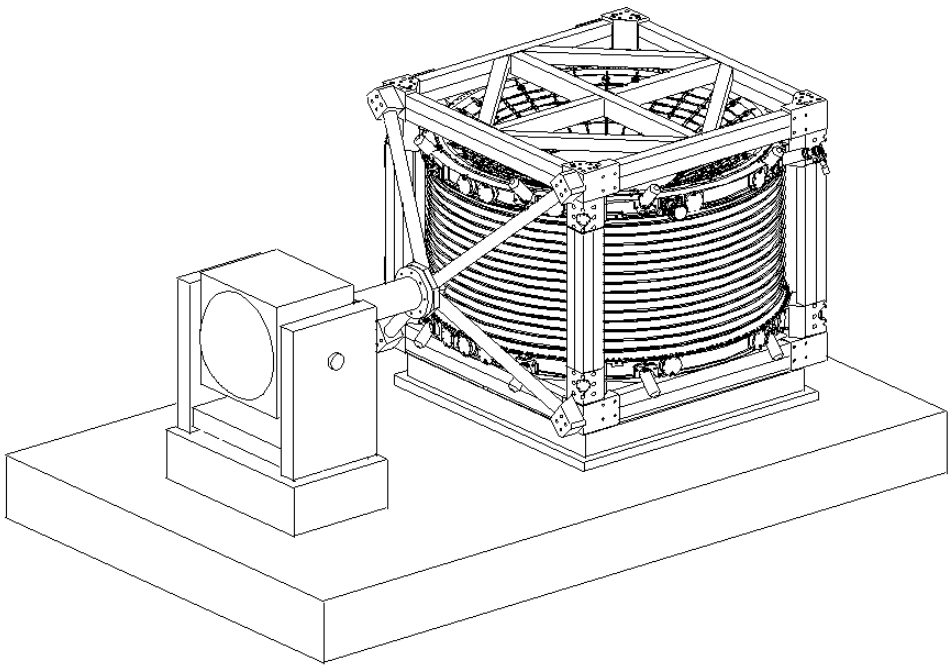
Warm Strap Static Failure Test



Cold Strap Static Failure Test

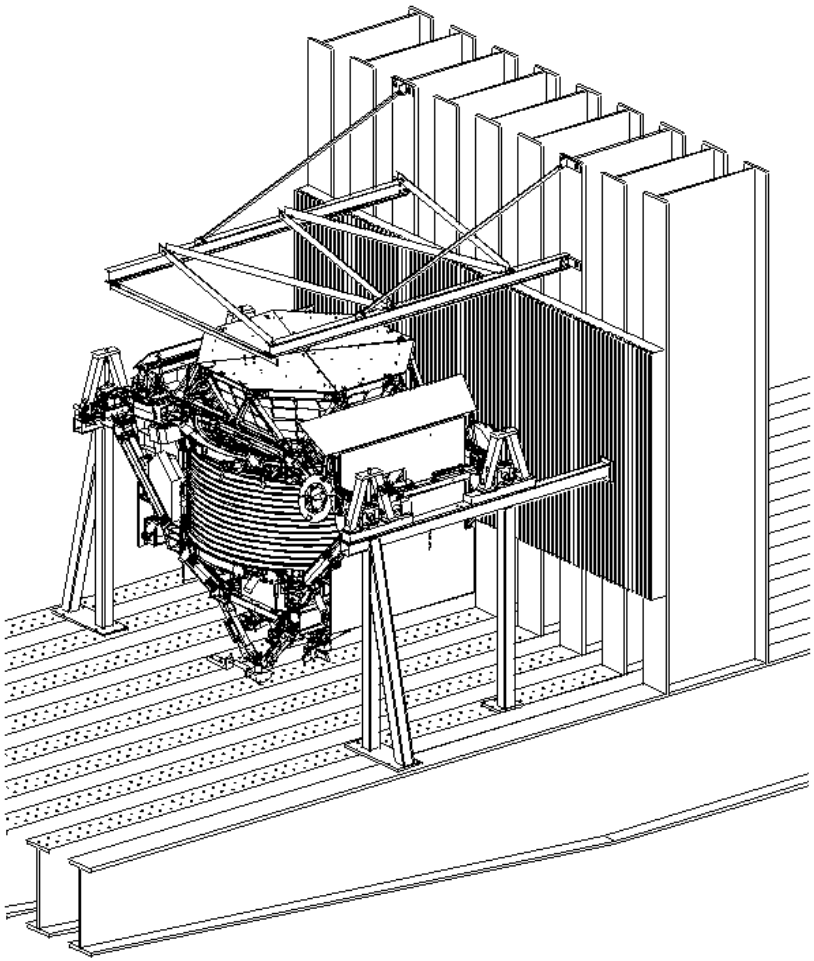
- Strap will be attached to actuator and the cold end be cooled to cryogenic temperatures.
- Primary goal is verification of cold force-displacement characteristics and ultimate strength.
- Test still in early planning stages.

Sine Sweep Test



- Test article is STA vacuum case and straps with mass simulated magnet.
- System will be swept at flight-like load levels in each axis:
  - ~0.5g in x-axis
  - ~0.25g in y-axis
  - ~0.8g in z-axis.
- Primary goal is nonlinear response measurement at flight-like load levels.

Modal Test



- Standard modal test of entire AMS-02 structural system.
- Low level force input will minimize nonlinear effects.
- Primary goal is measurement of USS and VC modes
- Nonlinear modes of global system will be correlated based on high-level sine sweep test.

Strap Analysis Plan

- Strap analysis includes all standard reports:
  - Fracture analysis.
  - Stress analysis to design loads.
  - Loads analysis to verify design loads.
- Certain elements require special analysis to address NASA concerns.
  - Creep analysis for composite components.
  - Linearized/nonlinearized loads comparison.

Strap Fracture Analysis

- Straps checked for fatigue using spectrum defined in AMS-02 SVP.
- Spectrum for flight unit includes:
  - 87 hours of truck and air transport.
  - Three liftoff/landing cycles.
  - Five-year on-orbit lifetime.
- NASGRO analysis of metallic parts with scatter factor of 4 shows no fracture issues for AMS-02.

Creep Analysis

- SCL performed a strap creep analysis in July 2001.
- Strap creep for three year on-orbit lifetime and one year of ground operations expected to be 16.8 μin.
- Preload loss is ~2 lb of an initial 1700 lb.

Strap Stress Analysis

- LMSO performed full stress analysis using design loads for strap pins and clevises.
- No negative margins found.
- Analysis being reviewed as component mass properties and math models are updated and design matures.

Strap Minimum Margins

Item	MoS (Ult)	MoS (Yield)	Failure Mode
Racetrack End Frame Clevis	+0.03	+0.45	Tension Load on Lug
Racetrack End Frame Pin	+0.06	+0.05	Bending
Cold Link Central Clevis	+0.15	+0.23	Shear Bearing
Cold Link Central Pin	+0.63	+0.21	Bending
Warm Link Central Clevis	+0.05	+0.13	Shear bearing
Warm Link Central Pin	+0.41	+0.05	Bending
Warm Link Bod Clevis	+0.14	+0.21	Shear bearing
Warm Link Bod Pin	+0.32	+0.30	Bending
Carbon Band	+0.67	-	Tension
FGR-3 Band	+2.1	-	Tension
Glass Band	+1.5	-	Tension
Glass Bod	+0.58	-	Tension

Strap System Models

- Several AMS-02 math models being developed
  - Full nonlinear MSC/Nastran model for design loads and stress analysis.
  - Simplified nonlinear Excel/Matlab models to assist in sensitivity work, trade studies, and linearization work.
  - Linearized model for use in the Verification Loads Analysis.
- All nonlinear models will be correlated to test data as well as each other.
- Linear model will be shown to predict loads that envelope nonlinear results.

Nonlinear NASTRAN Models

- Nonlinear FEM developed using ICD strap curves.
- Straps modeled as CROD elements with exact strap force-displacement relationship using TABLES1.
- Current model has 360,000 degrees of freedom.

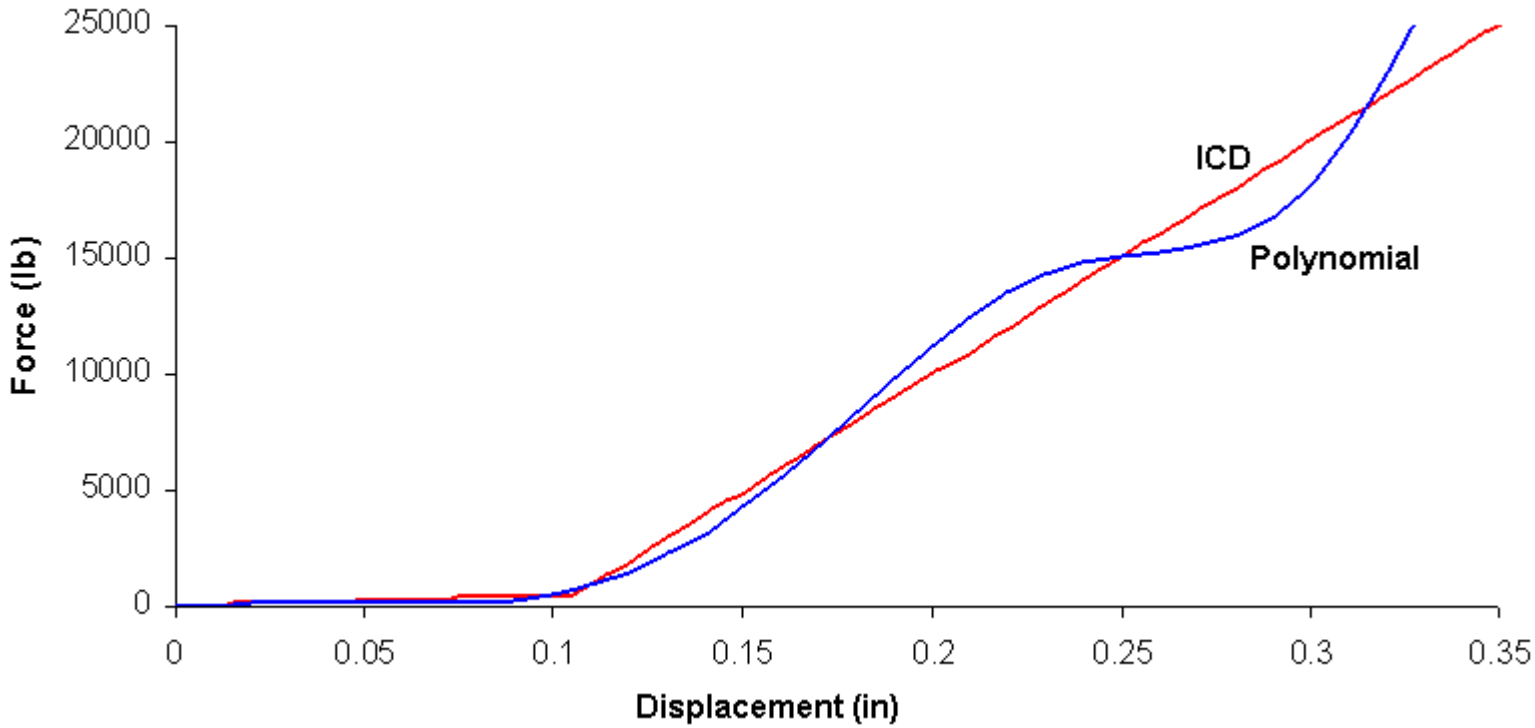
Polynomial Model

- Simplified polynomial models developed using method of multiple scales.
  - Method of multiple scales requires polynomial approximation of stiffness curve.
- First model created for 1-D dynamic test configuration.
- Next model will be six-DOF, 3-D full AMS-02 configuration.

1-D Dynamic Test Polynomial Model

- Curve for strap dynamic test analysis derived using modified least-squares approach.
  - Linear stiffness terms forced to match Region I stiffness properties. Nonlinear effects forced to be third-order or higher.
  - Curve forced to pass close to the knee point.
- 11^{th} order polynomial provided first reasonable fit.

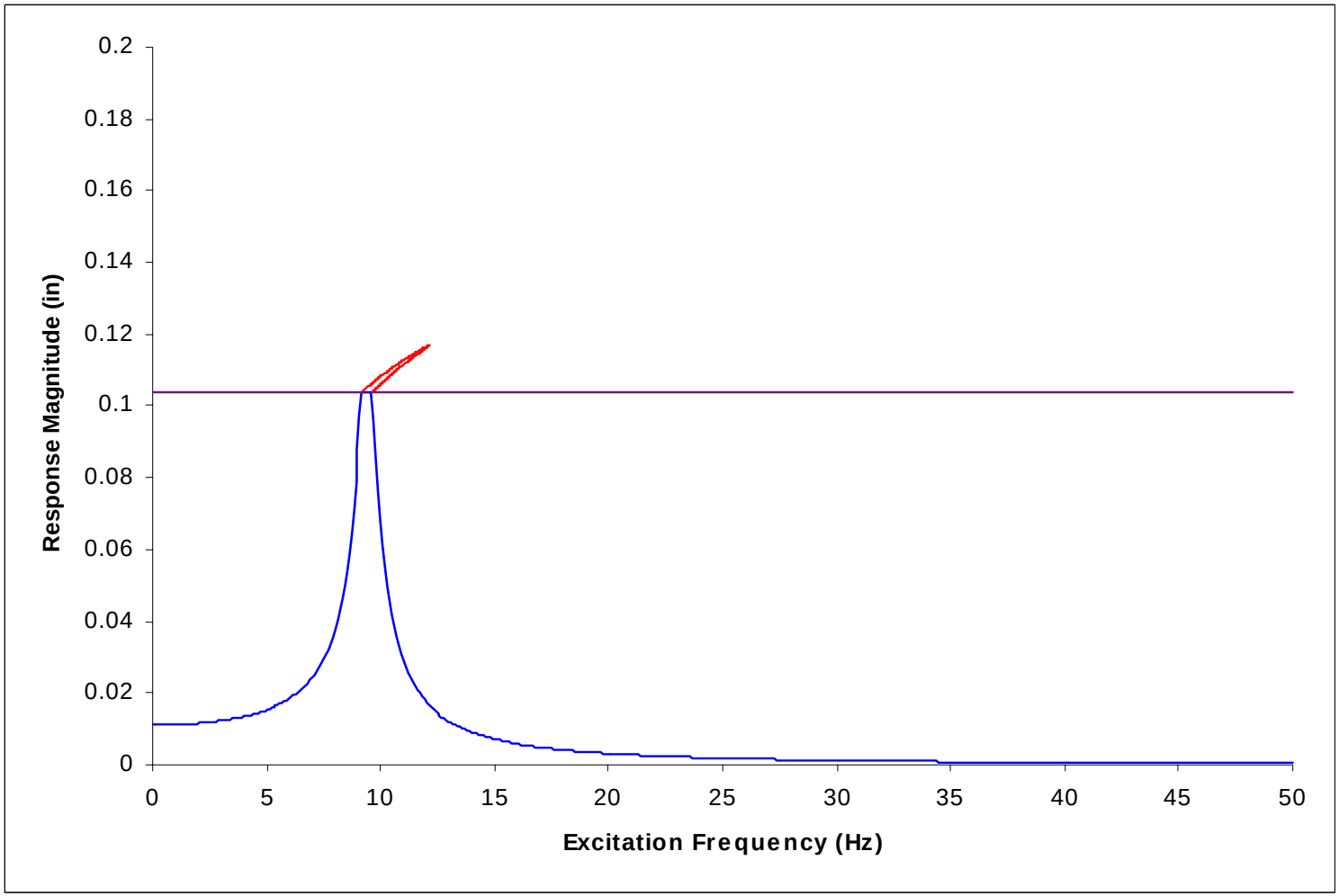
1-D Dynamic Test Polynomial



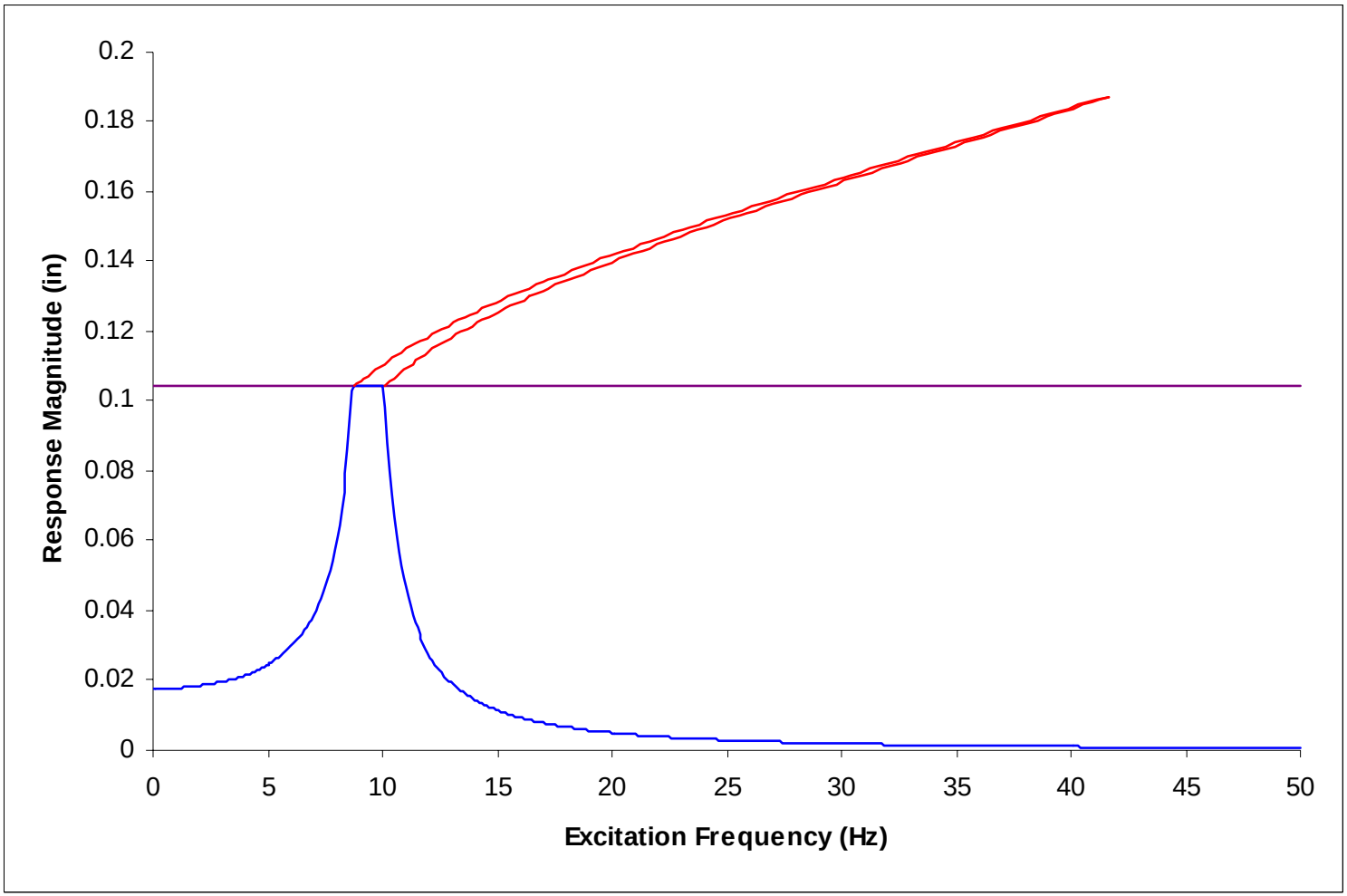
Analytical FRF Predictions

- Frequency response functions predicted for test system for several excitation load levels.
- Three types of valid solutions
  - Region I linear solution (blue line)
  - Primary resonant nonlinear solution (red line)
  - Superharmonic and subharmonic nonlinear solutions (green lines)

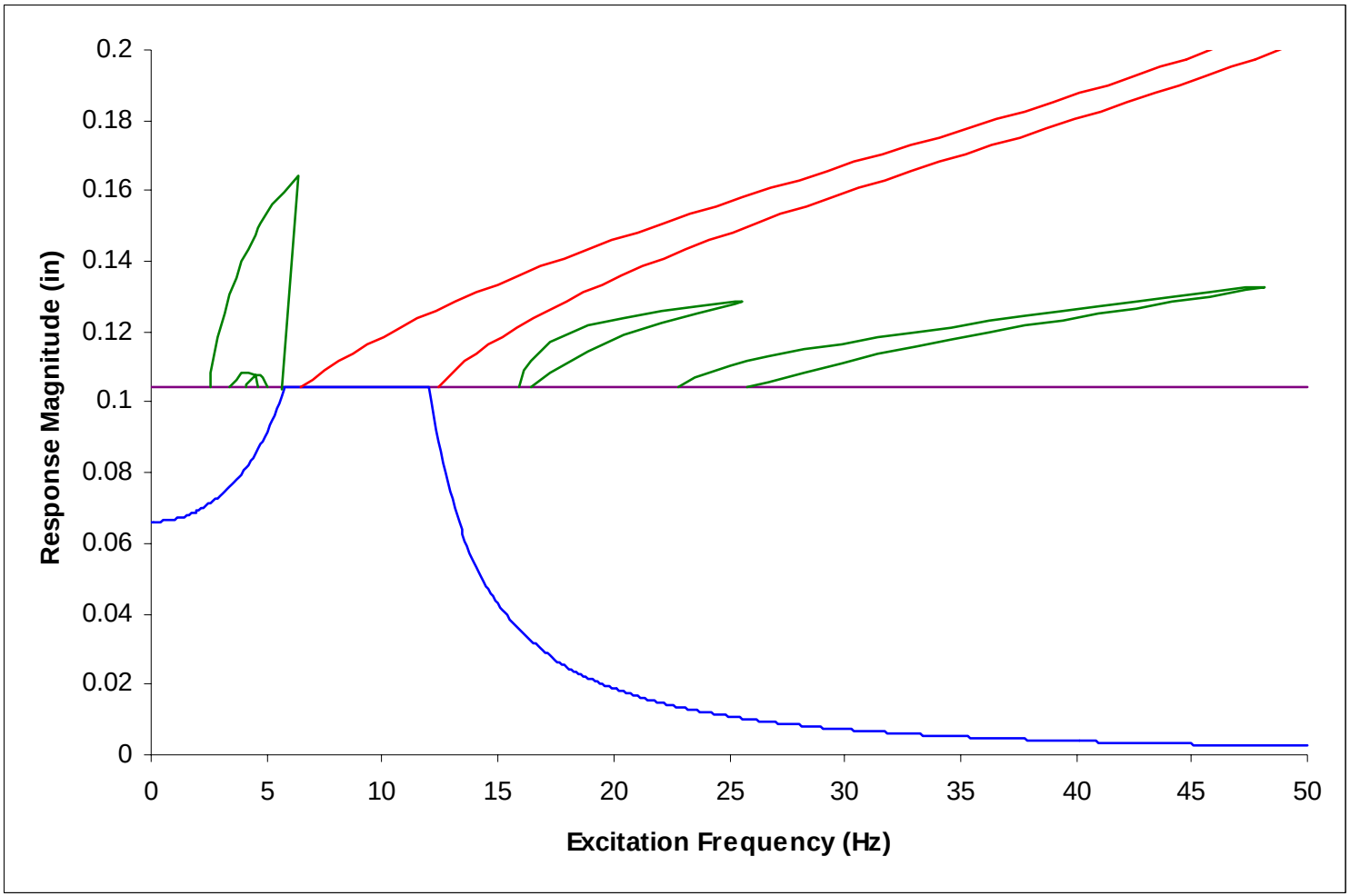
FRF – 50 lb Excitation



FRF – 80 lb Excitation



FRF – 300 lb Excitation



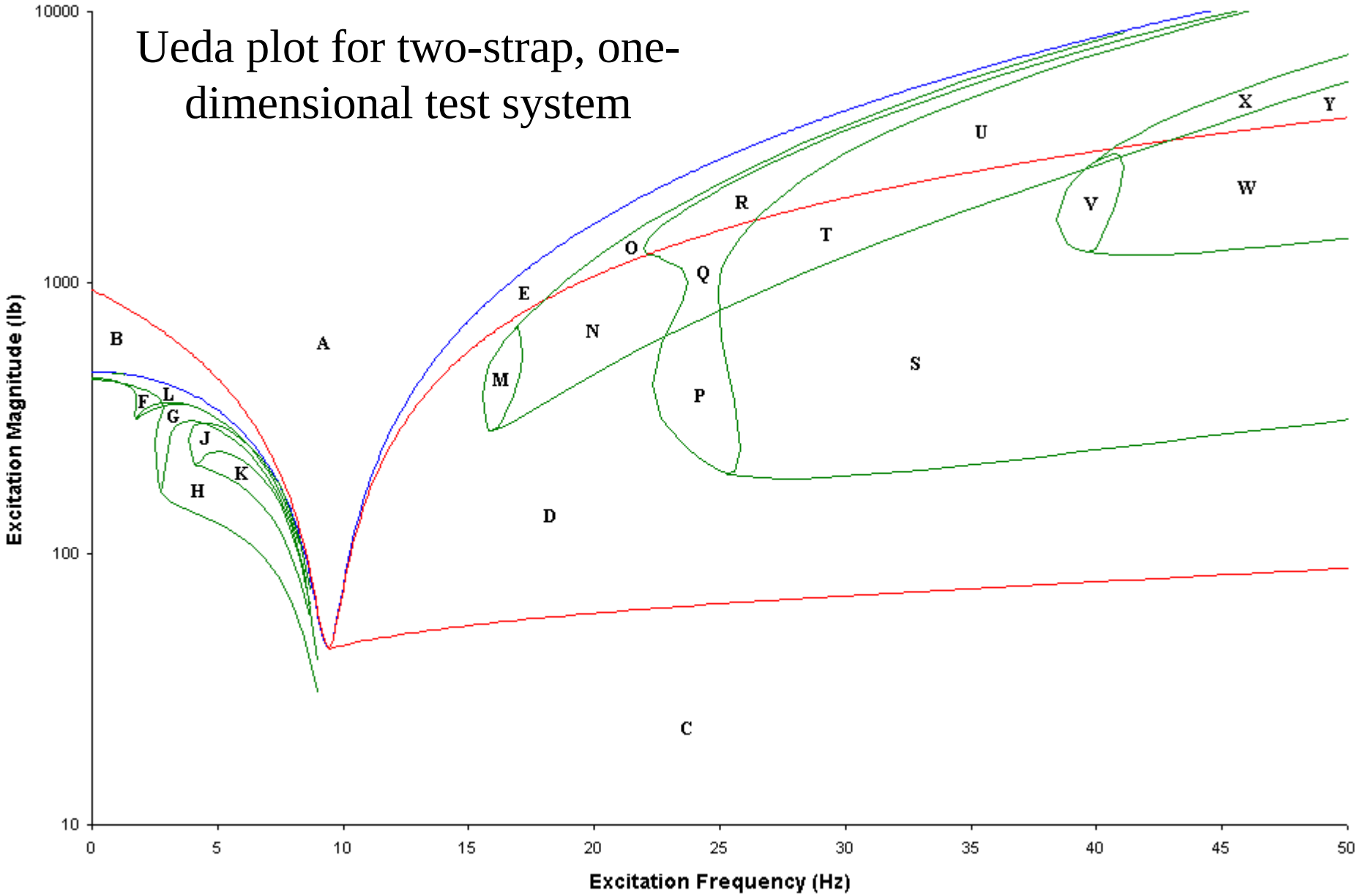
Valid Solutions

- For a given excitation load level and excitation frequency, there are a variable number of valid solutions.
  - Region I linear solution only valid below knee point.
  - Primary resonant nonlinear solution and superharmonic/subharmonic solutions only valid above knee point.

Ueda Plots

- Ueda plots show number of valid solutions for any given load level and excitation frequency.
- Regional boundaries determined by where various solutions cross knee point.
- Verification of this plot for two-strap system was primary goal of 1-D dynamic test.

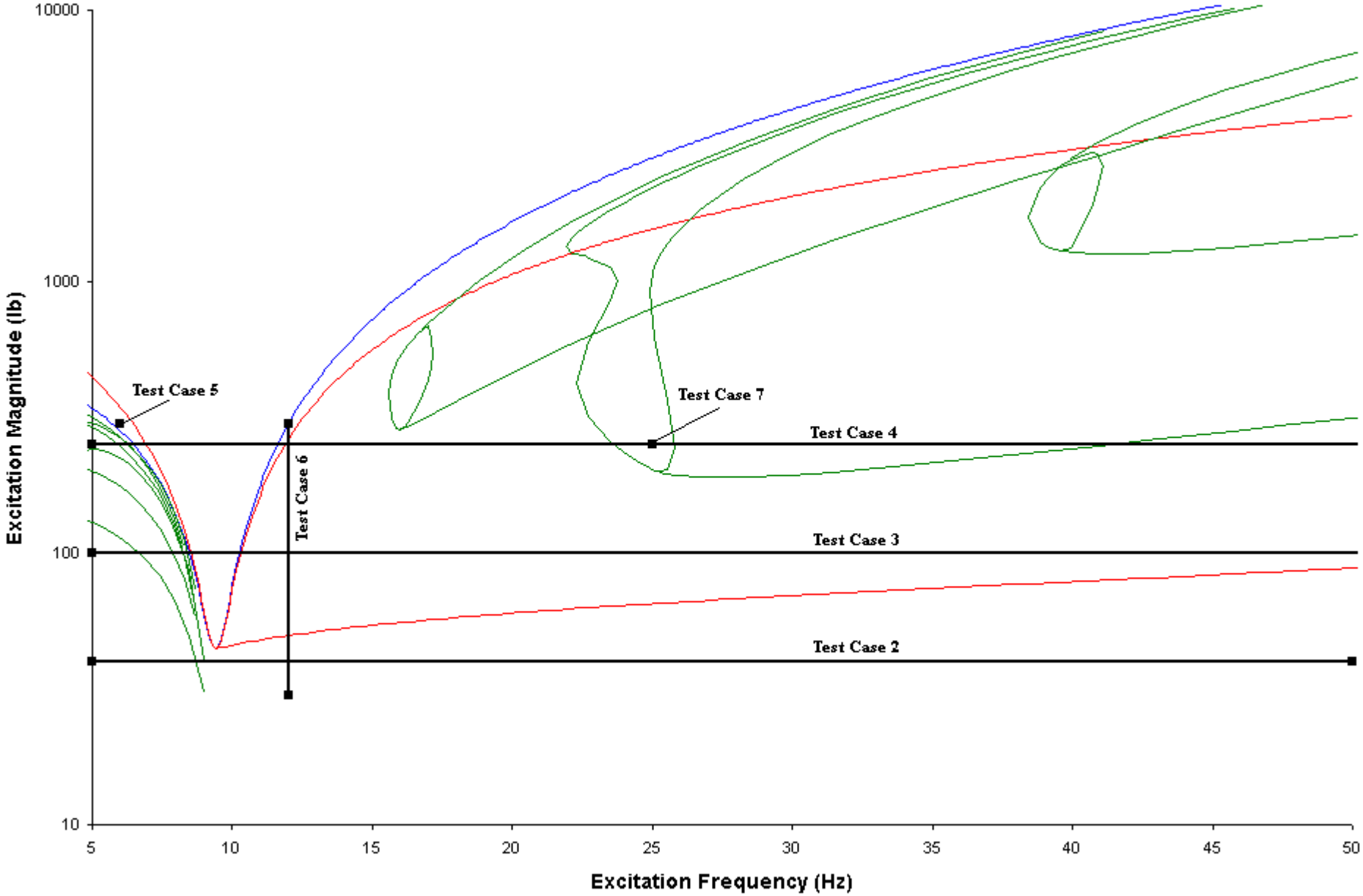
Ueda plot for two-strap, one-dimensional test system



Space Cryomagnetics

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

LOCKHEED MARTIN



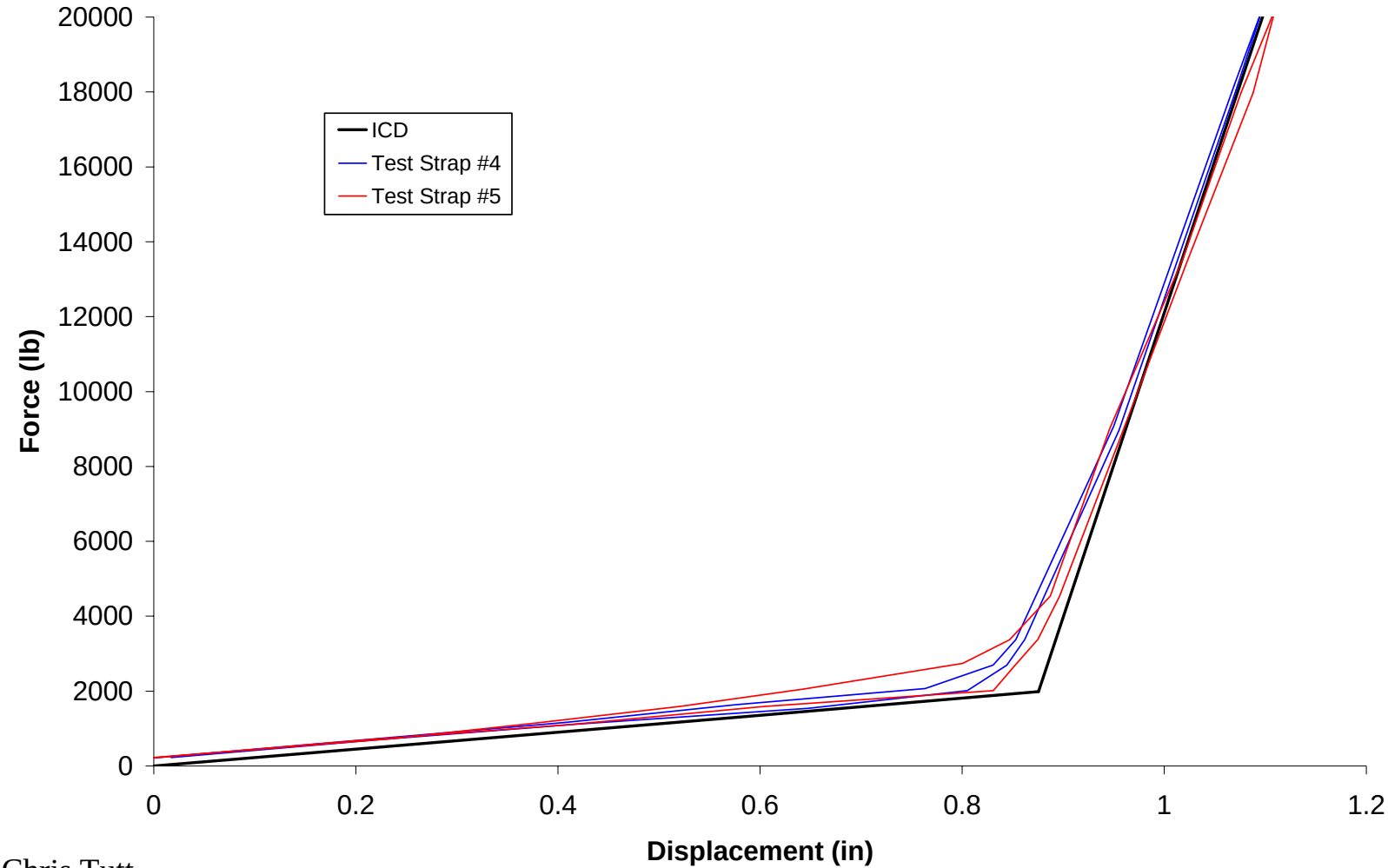
FEM-Polynomial Comparisons

- Nonlinear transient analysis has been performed using MSC/NASTRAN to provide initial check on polynomial model.
- Comparisons of steady-state magnitudes quite good.
  - Region I linear solutions match within 0.40%.
  - Primary nonlinear resonant solutions match within 2.02%.

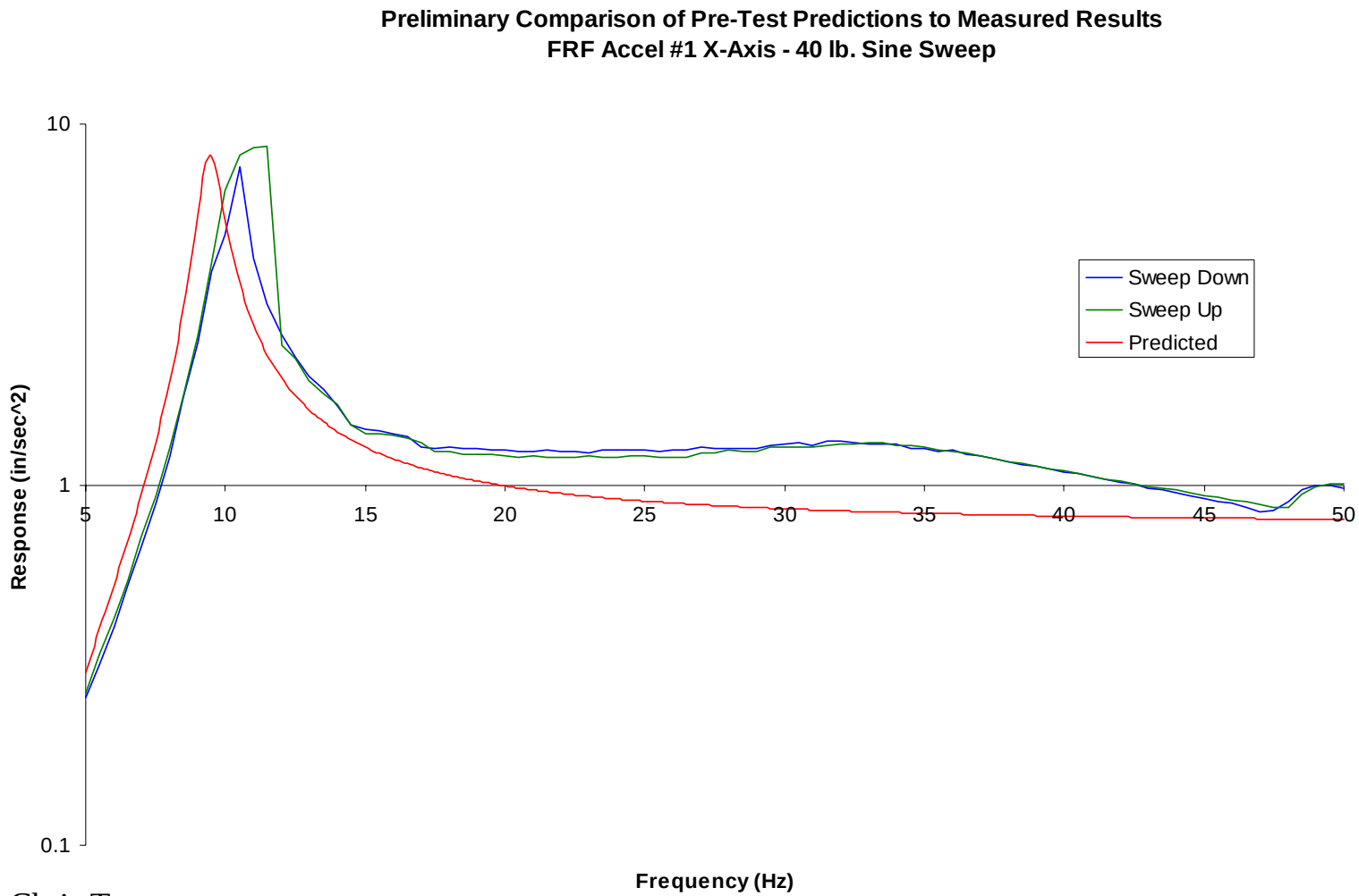
Test Results

- Three full strap tests completed to date:
  - Strap fatigue test (August 2002)
  - Strap static test (March 2003)
  - 1-D dynamic test (April 2003)
- All results being used to update analysis.
- Warm static failure test is next on schedule.

C1W1 Warm Static Curve Comparisons



Frequency Response Comparisons



Damping Measurements

- Results from initial 1-D dynamic test show Region I damping of ~14%.
  - High damping most likely due to friction in Belleville washer stack.
- Nonlinear analysis using constant, conservative damping value equal to ~4.5% in Region I, 1% in Region II/III.
- Linearized model will use standard VLA damping schedule.

Future Work

- 1-D Dynamic Test Report to be released soon. Strap models will be correlated concurrently.
- Static Failure Test coming soon.
- STA strap construction and acceptance testing in 2003.
- Sine Sweep Test to determine nonlinear behavior of Vacuum Case.
- Modal Test of full AMS-02.

Support System Documentation

- CTG-SCL-130802 – Fatigue Test Report for Strap #2
- CTG-SCL-290802 – Fatigue Test Report for Strap #3
- LMSEAT 33848, 1-D Dynamic Test Plan
- LMSEAT 33892, 1-D Dynamic Test Pre-Test Analysis
- LMSEAT 34044, 1-D Dynamic Test Report
- CTG-SCL-240303C – Strap Static Test Report
- LMSEAT 33847, Warm Static Failure Test Plan
- Stress Analysis Report
- Fracture Analysis Report

Strap System Points of Contact

- Design, Manufacturing, and Assembly

  John Ross, +044-(0)-1235-463964, johnross@spacecryo.co.uk
- Nonlinear Dynamics Analysis and Testing

  Chris Tutt, 281-333-7634, chris.tutt@lmco.com
- Stress and Fracture Analysis and Testing

  Chittur Balasubramanian, 281-333-7518, chittur.balas@lmco.com